Data Analysis of the COMPTEL Instrument on the NASA Gamma Ray Observatory

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ABSTRACT

The imaging Compton telescope COMPTEL on the NASA Gamma Ray Observatory is a wide field-of-view instrument. The coincidence measurement technique in two scintillation detector layers requires specific analysis methods. Straightforward event projection onto the sky is impossible. Therefore detector events are analyzed in a multi-dimensional dataspace using a gamma-ray sky hypothesis convolved with the point spread function of the instrument in this dataspace. Background suppression and analysis techniques have important implications on the gamma ray source results for this background limited telescope.
The COMPTEL collaboration applies a software system of analysis utilities, organized around a database management system. The use of this system for assistance of guest investigators at the various collaboration sites and external sites is foreseen and allows different detail levels of cooperation with the COMPTEL institutes, dependent on the type of data to be studied.

INTRODUCTION

The COMPTEL instrument as part of the NASA Gamma Ray Observatory, and its instrumental characteristics, have been described in detail by Schönfelder *et al.*, 1984. Instrumental performance and characteristics are presented by den Herder *et al.* (this volume). For details of calibrations and application of the instrumental response see Diehl *et al.*, 1991. The processing and analysis software environment COMPASS is described by den Herder *et al.*, 1991.
COMPTEL data analysis proceeds in three major steps:
1. Calibration processing of raw data
2. Response and background determination
3. Scientific Analysis
The raw data processing translates the raw telemetry data into normalized

and sorted databases (e.g. attitude data, housekeeping rates, event messages with calibrated and normalized parameters). After this step, the resultant data products (called 'level I data products') can be interpreted without particular knowledge of the data recording characteristics and stability performance of the instrument.

The second step is the analysis of the normalized event messages in terms of the instrumental response. Here a study of the signatures in the data is performed, the results are compared to prelaunch calibration data and other prior instrumental knowledge. Correlation studies of features in the dataspace spanned by all measured parameters of the events (e.g. signal pulse shape and time-of-flight) and instrument background environment (e.g. veto detector rates, cutoff rigidity) are performed on the flight data to establish models for the instrumental background. Here symmetry characteristics of the instrument are exploited to extract and smooth the background model. During this analysis the selection criteria for event messages are optimized. The resulting data products (response, background) constitute the second set of 'low level' data ('level IIa') needed for analysis.

The third step of analysis then combines the event data with these response and background matrices. Initially, a 'generic' skymap without specific astrophysical model assumptions is generated (via the Maximum Entropy Method). Hopefully this map gives indications of interesting regions, and the real in-depth scientific analysis begins: astrophysical models and their specific parameters are tested against the COMPTEL data, and parameter significance limits are derived. Maximum Likelihood based testing of the source models is applied in this dataspace to determine significances of the detected features and their parameters. In the course of these activities, selection criteria may be further optimized to improve the signal-to-background ratio for a specific topic under study; this leads back to the previous steps of re-generating applicable response and background matrices. The COMPTEL collaboration will assess the overall consistency of analysis steps, methods and selection criteria, before releasing the baseline set of results and data products (skymap; result parameter table; filtered event set; selection criteria; background matrices; response matrices) to the scientific community.

RESPONSE CHARACTERISTICS and ANALYSIS METHODS

The COMPTEL instrument operates in the range of MeV photons. Here the main photon interaction with matter is the Compton scattering process, thus dominating the response of the instrument. But this regime is also the domain of de-excitation radiation of atomic nuclei; this results in substantial contamination of the measured data with instrumental background events which do not originate in a Compton scatter interaction as quantified by the instrument response.

The interpretation of the telescope event messages is complicated further by the nature of the instrument response to photons from within the field of view:

For energies of about 1-2 MeV, the interactions in the instrument are mainly a single Compton scatter in the upper detector plane, followed by absorption of the scattered photon in the lower detector plane. This results in a fairly narrow 'source cone' signature of measured event parameters (see figure 1). However the Compton tail of the response of the scintillation detector results in event scatter angle measurements larger than the true scatter angle, forming a

'halo' in the inner part of the 'source cone' signature. At higher energies, the single Compton scattering competes with pair production as first interaction, resulting in a halo around the source cone in all directions. Similar halo events are produced at higher photon energies also by the increasing probability that the Compton scattered electron may produce bremsstrahlung photons, or may escape the scintillator. These response characteristics of the instrument are handled appropriately with the analysis methods operating in the full dataspace shown in figure 1; 'event circle' methods which just explore the main cone feature of the response can be used to confirm the more complex deconvolution method results, but only for strong, widely separated sources.
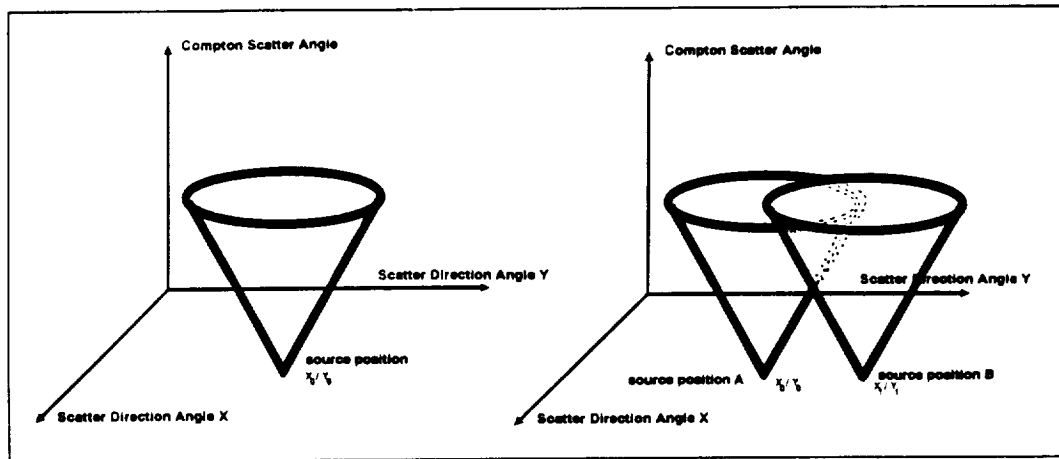

Fig.1 (left): *Dataspace for imaging analysis of COMPTEL data. The first order signature of a source is shown*

Fig.2 (right): *Overlapping measurement signatures from widely separated sources*

The azimuthally undetermined arrival directions of photons along a source cone also imply that source photons from very different directions in the sky may produce identical measured event parameters (see figure 2). Therefore the results of analysis of a particular sky region depend on the source assumptions in sky regions which are tens of degrees away. The standard analysis method should always involve a complete model for the entire instrument field of view.

ANALYSIS ILLUSTRATIONS

In the initial phase of the GRO mission, several cosmic gamma ray bursts were observed within the field of view of COMPTEL. Figure 3 displays the events from a burst (June 1, 1991) as distributed in the measured dataspace; the cone pattern can be traced in the form of rings of increasing diameter in the different slices of the (vertical) scatter angle axis. (Note that the large gamma-ray flux of cosmic bursts provides virtually background-free data, so that instrumental response features show up in the data with little contamination.) Figure 4 shows
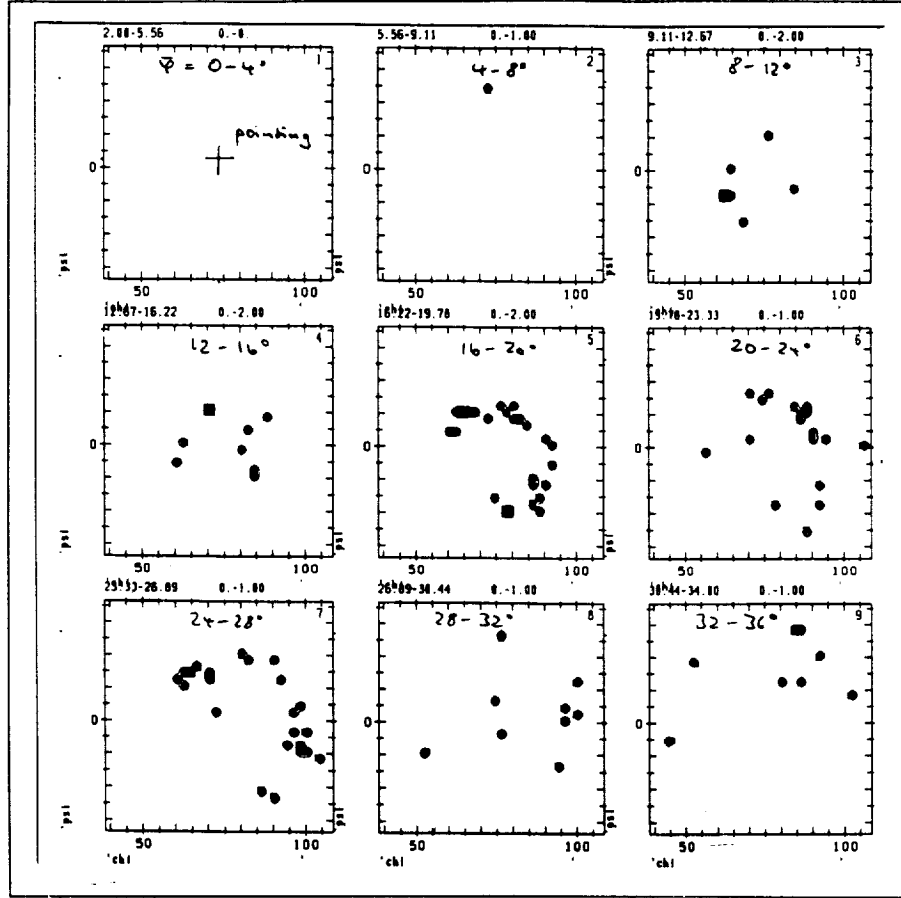
Fig.3: *Measured signatures from a cosmic burst (count diagrams in scatter directions are shown for different scatter angle slices). The cone signature is visible as a set of (inhomogeneously exposed) rings*

the projected raw event messages displayed as 'event circles' of possible arrival directions on the sky. These circles assume a Compton scatter interaction in the upper detector, and a total absorption of the scattered photon in the lower COMPTEL detector. Clumping of the event circle intersections can be seen at l=170, b=10 degrees. The Maximum Entropy deconvolved skymap using the full response detail (shown in figure 5) clearly shows that the sky is dominated by a single point source. Note that for these burst data any instrumental background is negligible.

In the normal case of imaging a complex sky region with the presence of substantial instrumental background, the analysis procedure is more complicated. Figure 6 shows a skymap generated with the same procedure as the burst skymap, namely ignoring background suppression and modelling. If no background knowledge is used at all, the skymap shows a wide range of structures; specifically a large extended structure is seen at longitudes 165-170 degrees. However, if the measurement of the time-of-flight is exploited to establish a background model via selection of events with time-of-flight values outside the
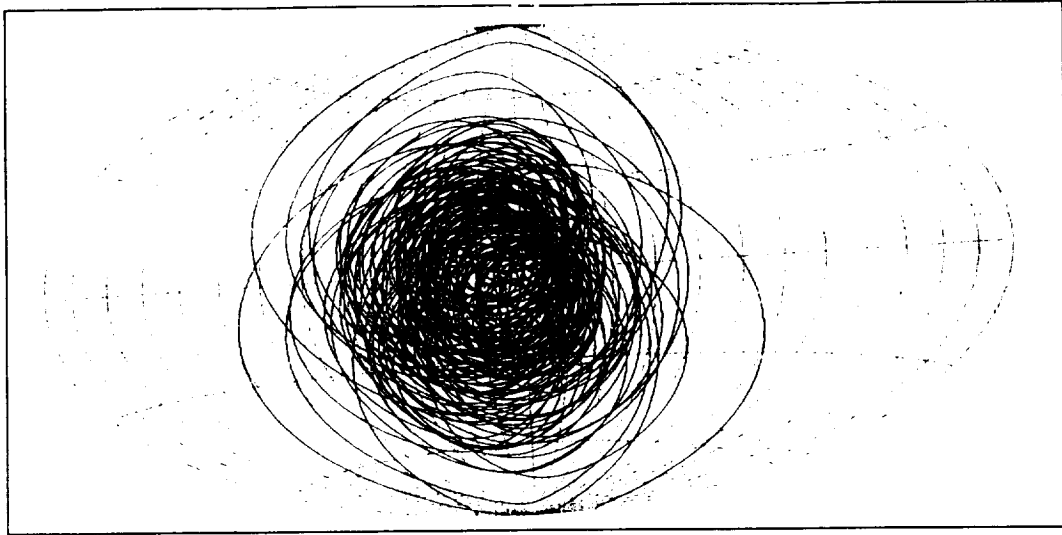
Fig.4: *Projected event circles measured from the cosmic burst 3 May 1991. Clumping of event circle intersections at the position of the burst is barely visible*
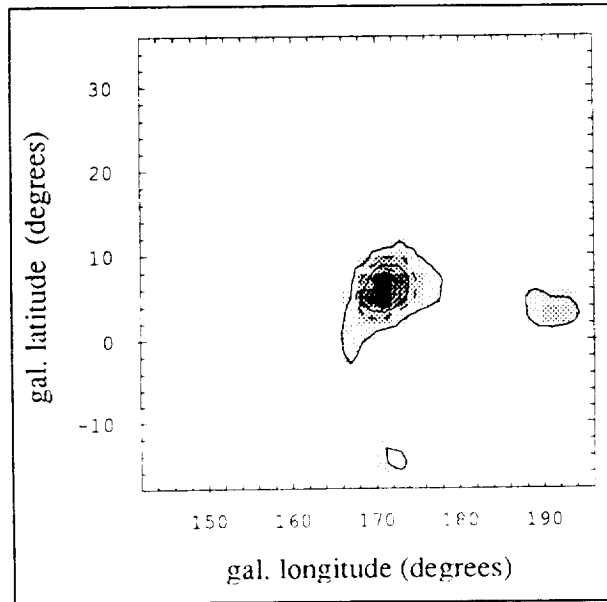

Fig.5: *Maximum Entropy deconvolved skymap from the cosmic burst 3 May 1991 using full response details*

normal values for forward scattering, this model can be applied in the analysis; the skymap in figure 6b is determined using this (crude) background information; obviously the large extended feature dissappears completely, while the dominating feature associated with the Crab nebula/pulsar remains.

Some detailed impacts of the response accuracy can also be demonstrated in the anticenter region (see figure 7). The COMPTEL point spread function can be determined in 3 different ways: via detailed calibration of the detecor
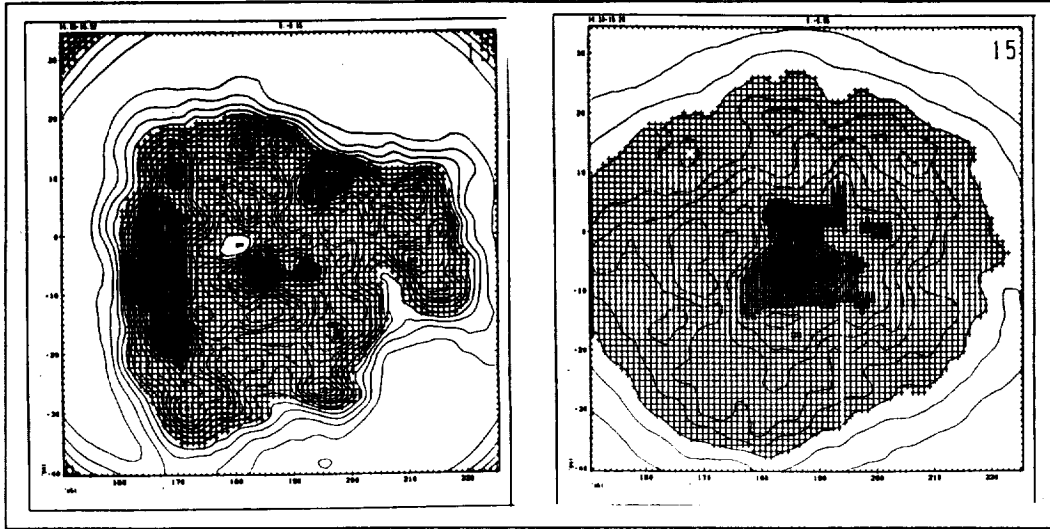
Fig.6: *Deconvolved skymaps from the anticenter region, illustrating the effect of background model inclusion. Without background modelling (a), left), and with inclusion of a coarse background model only, where the false feature dissappears (b, right)*
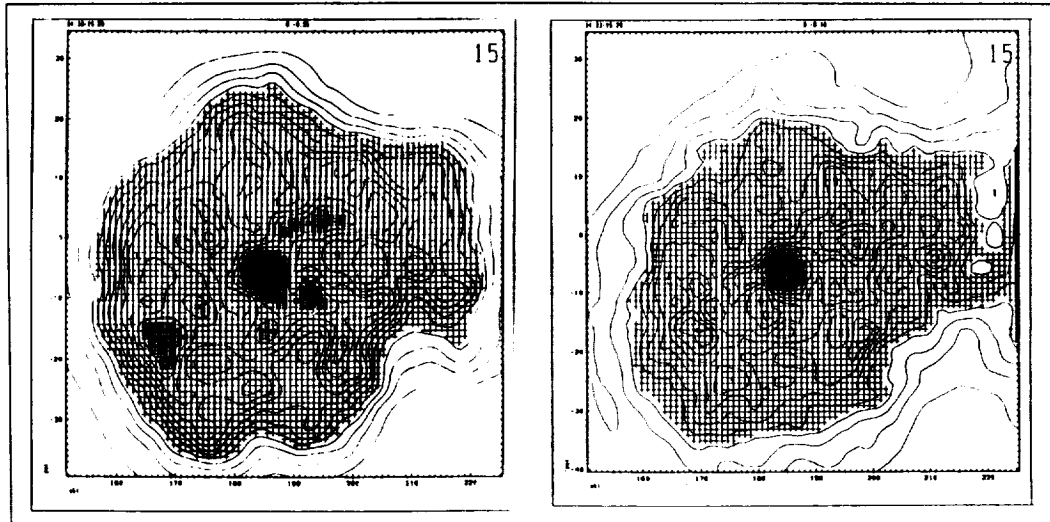

Fig.7: *Deconvolved skymaps from the anticenter region, illustrating the effect of different point spread functions. (Details see text)*

components and an analytical response calculation based on these detector characteristics, via sample calibration within the entire instrument field of view, or via simulations of the entire instrument. The analysis of the first observations (Crab at different aspect angles) will help determine which method actually describes the in-flight response most accurately. Figure 7 shows how the 2 different calibrated responses modify details of the skymap: The PSF used in the lefthand picture is based on accurate calibrations of the 21 COMPTEL detector modules, and on an analytical response calculation; this may ignore unknown secondary features of the true response. The PSF used in the righthand picture

is based on a few calibrations of the entire COMPTEL telescope field of view; this may include calibration contaminations due to the accelerator radiation environment and the non-parallel calibration photon beam. Clearly care must be applied in astrophysical interpretation of the small scale features: these could possibly be artifacts produced by interference of instrumental background and response imperfections as compounded in the complex deconvolution process. The COMPTEL collaboration analyzes details of the Crab image from different aspects, and exploits burst data, in order to optimize response and background treatment in the analysis, so that generation of such artifacts will be largely eliminated.

SUMMARY

The COMPTEL instrument aboard the NASA Compton Gamma Ray Observatory provides a unique opportunity for astrophysicists to enhance our present information about the gamma ray sky and about objects traceable via MeV gamma radiation. The large field of view of the imaging instrument, its operation in a high background environment, and its multiple-interaction based detection principle, necessitate sophisticated data analysis methods and procedures. First analysis results demonstrate the complexity of the analysis approach. Nevertheless the powerful analysis tools and methods established by the COMPTEL collaboration succeed in imaging the MeV sky, demonstrated with the 3 May 1991 cosmic gamma ray burst, and the Galactic anticenter region.

COMPTEL data products will be made available to the scientific community via the GRO Science Support Center. The complexity of the analysis requires care in the interpretation of these products and suggests that scientists should work in close association with the COMPTEL collaboration to benefit from our acquired expertise. Different levels of involvement are proposed and supported (for details see Diehl *et al.*, 1989 (1. GRO Science Workshop).

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